# AN EXPERIMENTAL STUDY OF A HYPERSONIC WIND-TUNNEL DIFFUSER

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# An Experimental Study of a Hypersonic Wind-Tunnel Diffuser*

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ABSTRACT

Results of a variable-area diffuser investigation in the continuous 12- by 12-cm. Naval Ordnance Laboratory Hypersonic Tunnel No. 4 are presented. A brief introduction discusses previous supersonic diffuser work. The diffuser investigated and the experimental technique are then described. The results show that air condensation in the test section at high Mach Numbers has only a minor effect on diffuser performance. Data on overall pressure ratios for starting and maintaining hypersonic flow for a number of diffuser configurations are presented. The test Mach Numbers range from 5.9 to 9.6. From these data, a diffuser with a single-peaked throat and a three-degree plane wall divergence aft of the throat was selected as most practical. The pressure recovered by this optimum diffuser varies, depending on Mach Number, from 1.8 to 2.3 times that recovered by a pitot (or impact) tube operated at the test-section Mach Number. Data on pressure-distribution measurements throughout the nozzle and diffuser, spark schlieren photographs of diffuser flow, and data on Reynolds Number effects are also given. Finally, these data are compared with those of other investigators and with one-dimensional theory.

## INTRODUCTION

A MAJOR COMPONENT OF supersonic wind tunnel working sections is the diffuser that decelerates the flow from supersonic to low subsonic speeds. A review of this problem is given by Ferri.[1] Diffusers do not operate free of losses, and their performance is characterized by indicating their overall pressure ratios ($p_0/p_e$, see Fig. 1) or pressure recovery. This is sufficient because the air leaving the diffuser has practically wind-tunnel supply temperature. A low overall pressure ratio or high pressure recovery is then desirable for wind-tunnel power-plant operation. This operating pressure ratio is different for different types of diffuser and test-section configurations. It is also a function of test-section Mach and Reynolds Numbers.

Many supersonic wind tunnels have diffusers designed primarily on the basis of subsonic experience, resulting in high overall pressure ratios.[2] Diffuser end pressure in these cases is below test-section pitot pressure. (A pitot tube decelerates the flow through a normal shock and a subsequent isentropic compression.) This lower recovery is due to the fact that, aside from a normal shock, viscosity effects in the diffuser introduce additional losses, thus lowering the end pressure. Since a diffuser employing a system of oblique shocks should have a better pressure recovery than one with a single normal shock, efforts were made to improve supersonic wind tunnels along these lines. This method had already proved successful in ram-jet diffusers. Variable-area diffusers whose throats can be closed after flow has been established were of interest here because of their higher pressure recovery.

To the authors' knowledge, the first supersonic tunnel diffusers giving end pressures higher than pitot pressure were discussed by Kurzweg[3] and Neumann and Lustwerk.[4] Diggins (N.O.L., unpublished) extended Kurzweg's work up to a Mach Number of 4.9. The first hypersonic diffuser was investigated by Bertram.[5] His tests were carried out in the 11-in. Hypersonic Wind Tunnel of the N.A.C.A.'s Langley Laboratory at a Mach Number of 6.9. End pressures up to 2.1 times pitot pressure were achieved by him. The present

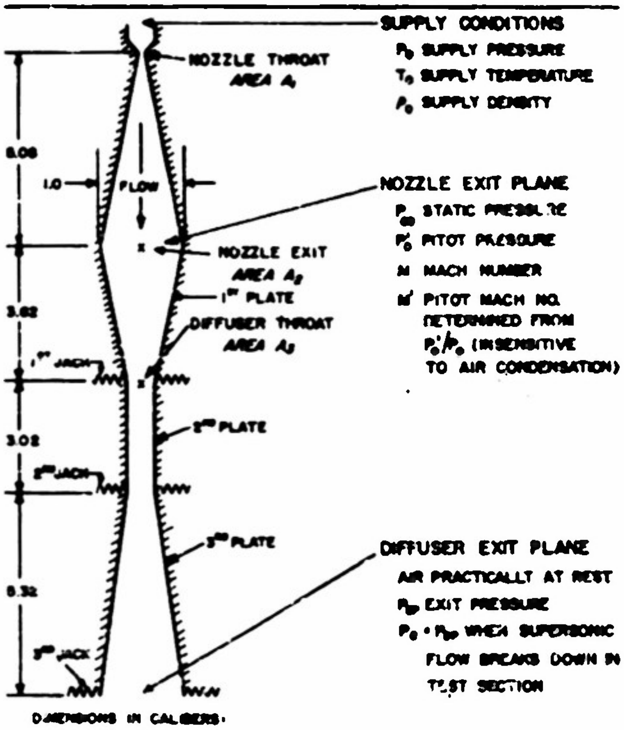


FIG. 1. Nozzle and diffuser dimensions, notation.

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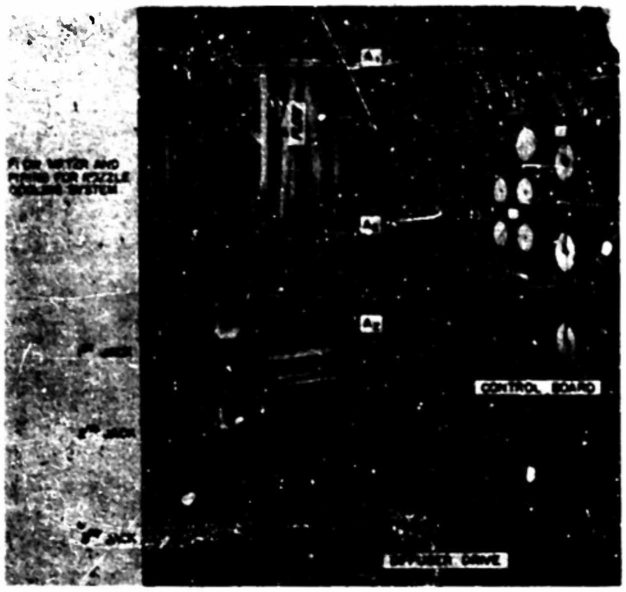


FIG. 2. Working section of the N.O.L. Hypersonic Tunnel No. 4.

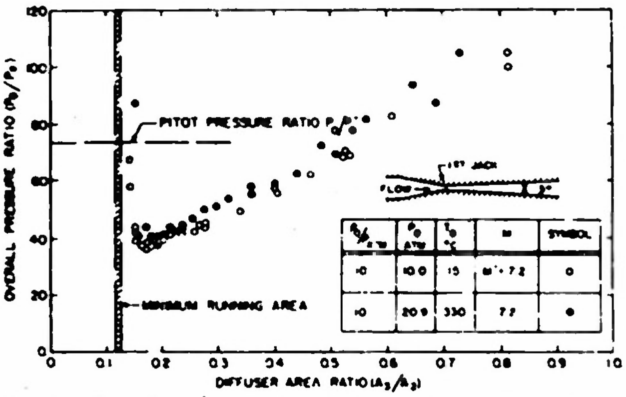


FIG. 3. Overall pressure ratios with and without air condensation.

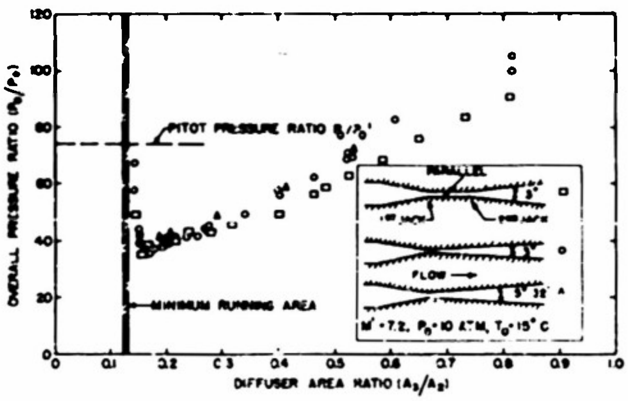


FIG. 4. Overall pressure ratios for three diffuser configurations.

investigation with a variable-area diffuser covers a Mach Number range from 5.9 to 9.6.

The overall pressure ratio needed for starting supersonic flow is important because it alone determines the maximum performance requirements for the power plant. At the present time little is known on this subject.[4–6] Starting requirements were also investigated and the results are presented.

Finally, it is interesting to note that, although the open jet diffuser type is amenable to theoretical treatment,[5] the closed jet diffuser of interest here cannot yet be treated by a unified theory. This is because the variation of pressure and shearing stress along the solid walls must be included in the analysis. Such a calculation would require presently unavailable knowledge of turbulent boundary-layer characteristics in coverging and diverging channels and an understanding of shock-wave boundary-layer interaction.

## Wind-Tunnel and Experimental Method

The continuous N.O.L. 12- by 12-cm. hypersonic tunnel[10] operates from a 3,000 lbs. per sq.in. supply of dried air. Pressure-regulating valves control the supply pressure of the tunnel in the range from 1 to 30 atmospheres. Electric heaters control the supply temperature of the tunnel in the range from room temperature to above 500°C. Heating of the air is needed if air condensation in the test section is to be avoided. A steel wedge-type nozzle with a built-in cooling system to maintain nozzle wall temperature at a low value during high-temperature operation expands the air to a desired Mach Number in the range from 5 to 10 (see Fig. 2). The Mach Number distribution in a traverse across the exit plane of this wedge nozzle, exclusive of the boundary layer, is uniform to within $\pm 0.01M$ at $M = 7.2$, the Mach Number for which most of the data are shown.

Each diffuser wall has three plates, the first of which is linked directly to the nozzle end. Because of the high Mach Number in the test section, the shock angle caused by the flow deflection at this point is small, and long models can be used without having the conventional parallel wall test section. Three pairs of jacks control the motion of the three plates with respect to the working section wall. Sliding gaskets of Silicone rubber stripping fastened to the diffuser plates seal the diffuser in all positions. A flexible compartment seal between the first plates and the outside tunnel walls keeps the air behind these plates at near test-section pressure. The diffuser can be operated electrically during the run from fully opened to fully closed position. The diffuser throat opening is recorded to within 0.005 in. Steel sidewalls with pressure taps along the centerline or walls with 1-in. thick circular commercial plate-glass windows enclose the diffuser. Photographs are taken with a spark light source of $^1/_2$-microsec. duration.

The diffuser leads into a 12-in. pipe connecting the tunnel to vacuum pumps. Since the high-pressure air supply lasts for hours and the vacuum pump capacity exceeds tunnel requirements, tunnel operation is continuous. Arbitrarily chosen overall pressure ratios can be established to the order of 1 per cent accuracy.

To determine operating conditions, supersonic flow was established with a high pressure ratio. (Pressure ratios of the order $10^4$ are available.) The diffuser throat was then closed to a point where supersonic flow broke down in the test section. After this minimum throat area had been established, minimum overall pressure ratios were measured for all diffuser throat areas larger than the minimum area. The overall pressure ratio ($p_0/p_e$) at the moment of "breakdown" of supersonic flow in the test section was noted. Flow breakdown was determined by any of three methods, which yield identical results: visual observation of the flow in the test section with the schlieren system, change of noise, and change of test section static and pitot pressure.

Minimum starting diffuser throat areas and minimum overall starting pressure ratios were determined in a similar manner.

### Operating Requirements

If a supersonic tunnel is operated from a reservoir of dry air at room temperature and pressure at $M > 4.8$, a fraction of the air will condense at, or shortly after reaching, its saturation point in the nozzle.[10, 11] Such air condensation affects the commonly measured flow parameters differently. In particular, static pressure is extremely sensitive and pitot pressure nearly insensitive to the presence of condensed air in the flow. Fig. 3 shows overall pressure ratios for one diffuser configuration and nozzle-area ratio. In one test the air was not heated and air condensation occurred. In the other test the air was preheated above the supply temperature needed to keep the thermodynamic state of the air outside the condensation region during the entire expansion process. (To minimize Reynolds Number effects in this comparison, the supply density was kept the same for both the high and low $T_0$.) It can be seen that overall pressure ratios in the case with air condensation are somewhat lower than in the heated case free of such condensation. This is to be expected since the actual flow Mach Number is higher in the "hot" case. However, the difference is small enough for engineering purposes to state that diffuser performance is nearly insensitive to air condensation as previously found for the performance of the pitot tube.[10] The following tests (except the sensitive static pressure measurements and checks on starting) were therefore made without preheating the air, and the Mach Numbers indicated as $M'$ are to be taken as those derived from the insensitive pitot measurements with the aid of a flow table. This procedure (of running the tunnel with cold air) makes it possible to photograph and observe the flow without the danger of cracking glass windows because of the heat. It also speeds up testing.

The pressure recovery of the diffuser in terms of pitot pressure over the range of Mach Numbers tested was generally of the same order. A detailed investigation was therefore carried out at the optimum Mach Number 7.2 only.

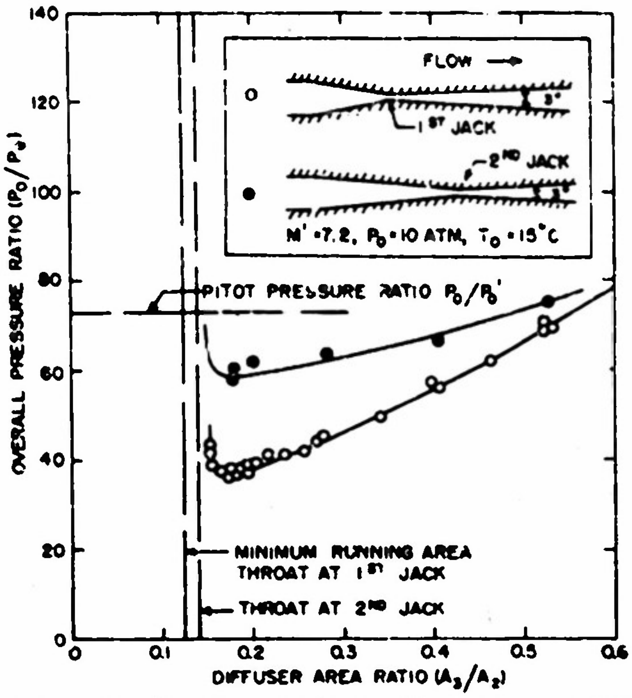


Fig. 5. Overall pressure ratios for two diffuser throat positions.

Overall pressure ratios as functions of diffuser-area ratio for three different diffuser configurations are given in Fig. 4. The Reynolds Number, based on tunnel width, for the comparable condition of no air condensation (Fig. 3) is 3,500,000. It can be noted that the case of parallel second diffuser plates[5] requires the lowest pressure ratio for large throat openings. No improvement is obtained when the angle between the second plates is increased from parallel to 1° to allow for boundary-layer growth. Diffuser performance is also practically unaffected if the angle between the third plates is increased from 3° to 14° and presumably flow separation takes place between the last plates. Fig. 5 gives a comparison of the pressure ratio for two different throat locations corresponding to the first and second jack position. It can be seen that the first throat position gives a better pressure recovery. It is assumed that in the second case the advantage of an increased number of shock reflections is more than offset by the increased friction along the longer duct.

A reduction of supply pressure increases the viscous effects at the diffuser throat. If the supply pressure is lowered, the minimum throat opening must be increased to accommodate the thicker boundary layer as shown in Fig. 6. It was also found that for a given diffuser throat an increase in supply pressure resulted in a decreased overall pressure ratio.

Fig. 7 gives a set of spark schlieren photographs taken with the configuration of a single peaked throat and subsequent 3° wall divergence. Pressure-ratio data corresponding to the conditions photographed in Fig. 7 are shown in Figs. 3 and 4.

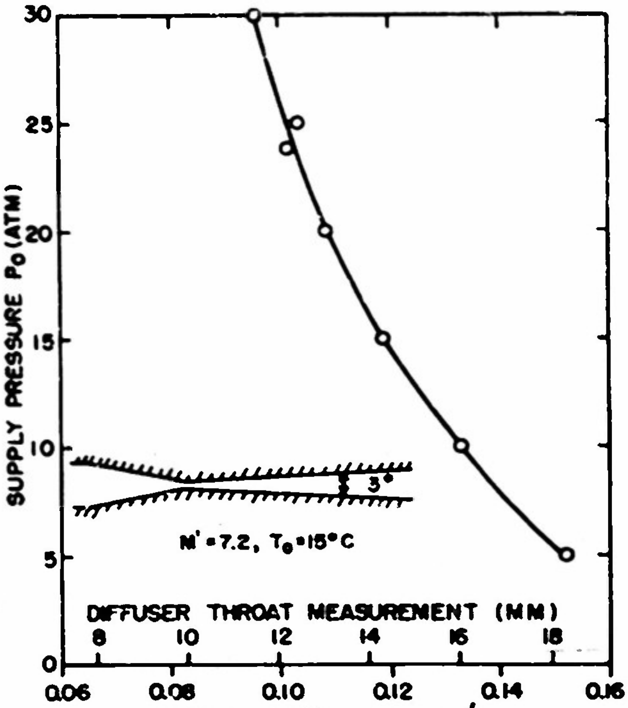


FIG. 6. Effect of supply pressure on minimum running area ratio.

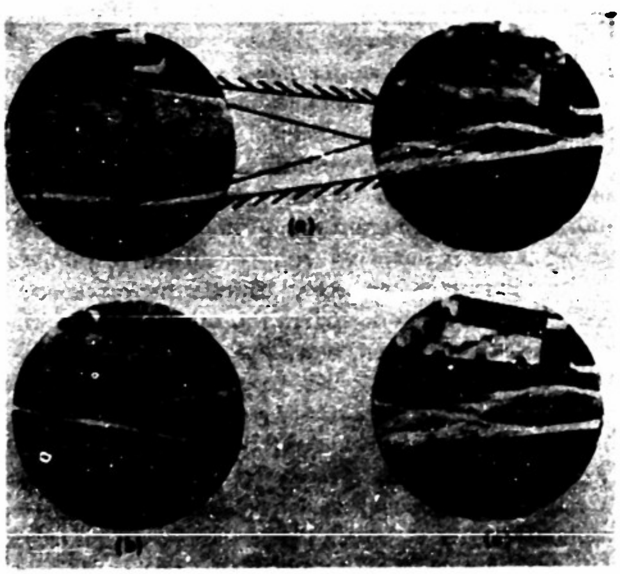

FIG. 7. Spark schlieren photographs of diffuser flow; $M' = 7.2$, $p_0 = 30$ Atm., $T_0 = 15$°C. (a) Test section and converging diffuser plates, $A_3/A_2 = 0.20$ (optimum); (b) converging diffuser plates, $A_3/A_2 = 0.60$; (c) converging diffuser plates, $A_3/A_2 = 0.40$.

In the photographs it may be noted that the boundary layers along the test section and diffuser walls are turbulent. This was confirmed by detailed pressure and temperature measurements in the layers with $T_0$ high enough to avoid air condensation.

Finally, Fig. 8 gives pressure distribution measurements taken along the sidewall centerline. These measurements were carried out with the supply air heated to $T_0 = 320$°, 30°C. higher than is needed to avoid air condensation throughout.

Diffuser data for the same configuration taken at other Mach Numbers as check points are presented in the collection of all available results in Figs. 12 and 13.

Using the data given above, we may postulate the following diffusion process: The oblique shocks emanating from the junction of first diffuser plates with the nozzle exit and their single reflection slightly ahead of the throat cause the significant increase in pressure. The Mach Number at the throat outside the large area taken up by boundary layers is still rather high (in the case of $M = 7.2$ in the test section it is of the order 4 to 5). Further diffusion from the throat to the end of the diffuser is relatively inefficient; in fact, it is about equal to that obtained in any diverging pipe with an entrance Mach Number of about that at the diffuser throat. Aft of the throat (see Fig. 8), transition to subsonic flow takes place through an oscillating shock system. Noise measurements at this point show a predominant frequency of the order of 5,000 cycles per sec. for a diffuser setting giving optimum pressure recovery. This frequency is a function of diffuser throat area, decreasing to about 1,000 cycles per sec. if the diffuser throat is wide open. Parallel second diffuser plates apparently contribute little to the stabilization of this shock system.[12]

Aside from structural reasons, it is desirable to eliminate the parallel section, because at $M = 1$ the product of density and velocity shows a maximum and, consequently, the heat transfer from the flow to the tunnel walls is maximized. This is important because of the high stagnation temperatures involved, resulting in the possible need for diffuser cooling systems in addition to nozzle cooling. This heat transfer was sufficient to cause glass cracks near the diffuser throat during heated runs.

In a further series of tests with cone cylinder, sphere and missile models, and supports in the test section, it

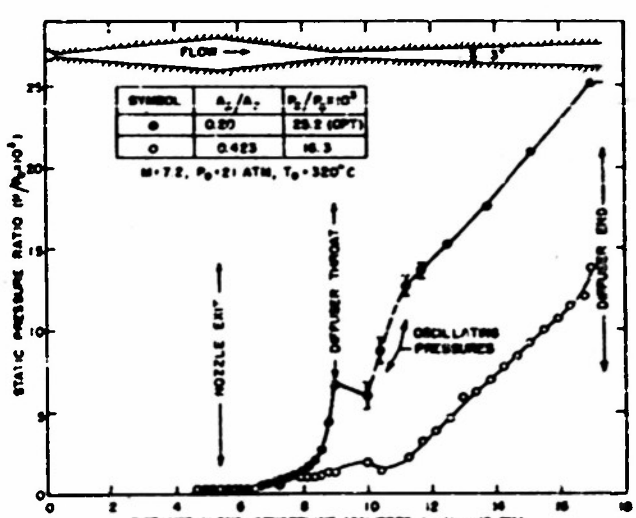


FIG. 8. Pressure distributions along centerline of tunnel sidewall.

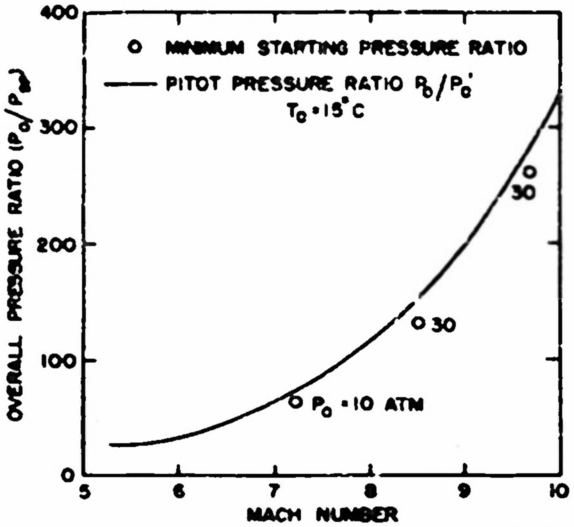


FIG. 9. Minimum starting pressure ratio vs. Mach Number.

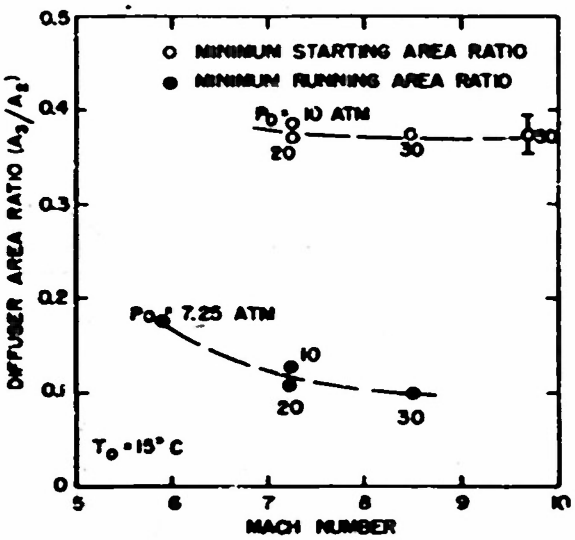


FIG. 10. Minimum starting and running area ratios vs. Mach Number.

was found that, aside from an increased minimum diffuser throat area, overall pressure ratios were little changed.[6] Apparently, the favorable additional oblique shock system introduced by the model counteracted the detrimental viscous effects due to surface friction and wake.

## Starting Requirements

Minimum pressure ratios and minimum area ratios to start the tunnel are shown in Figs. 9 and 10. It can be seen that, although the minimum starting area is appreciably larger than the minimum operating area, it is about one-third smaller than that predicted by one-dimensional theory.[1] If the diffuser throat is larger than the minimum needed to establish supersonic flow, the starting pressure ratios are nearly equal to those given previously for operation. The minimum starting pressure ratio is somewhat lower than the pitot pressure ratio for the test-section Mach Number, and it is considerably below the pressure ratios previously anticipated by hypersonic wind-tunnel designers. This result is important because it may eliminate costly additions to hypersonic tunnel power plants for the momentary attainment of extremely high pressure ratios. An effect of the rapidity with which flow was established could not be found. A distinction was made between a "slow" and a "fast" start. In the case of the "slow" start, the overall pressure ratio was slowly increased, while the tunnel operated subsonically. The pressure ratio at which steady supersonic flow occurred in the test section was noted. For the "fast" start, the starting pressure ratio was established within 1/500 sec. by means of the fast-acting valve. No change in this ratio could be found with respect to the previous test. During the starting process, a supersonic jet detached itself from one nozzle wall and passed into the diffuser as shown in Fig. 11. Only for sufficient pressure ratio did this jet spread to the full width of the nozzle. Neither the diffuser configuration nor the presence of models had an appreciable effect on starting requirements.

## Comparisons and Conclusions

The present results are compared with data from other diffusers in Fig. 12. A general increase of pressure recovery with Mach Number in terms of pitot pressure can be noticed. The drop at the highest Mach

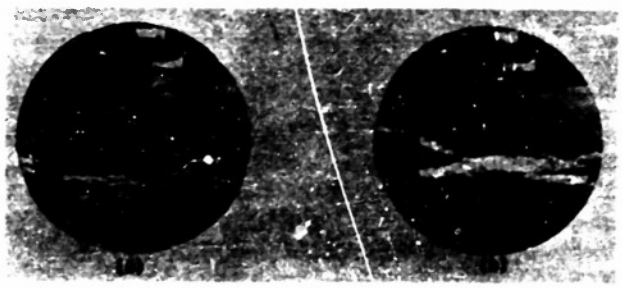

FIG. 11. Schlieren photographs of jet in test section before complete starting of tunnel; $p_0$ = 10 atm., $T_0$ = 25°C. (a) $p_0/p_w$ = 60.8 and (b) $p_0/p_w$ = 62.8. (Starting pressure ratio $p_0/p_w$ = 64.4; $M'$ = 7.2.)

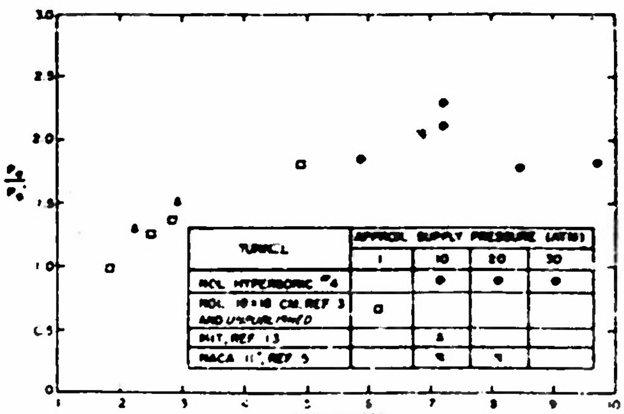


FIG. 12 Comparison of pressure recovery in terms of pitot pressure for several closed jet tunnels.

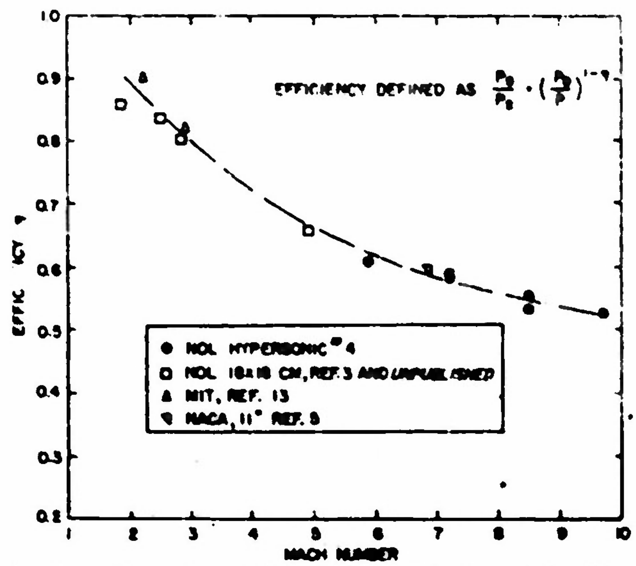


FIG. 13. Comparison of diffuser efficiency for several closed jet tunnels.

Numbers might be avoided by optimizing the length of the first diffuser plates. In fact, a special configuration would be needed for every Mach and Reynolds Number to attain the best performance. However, for practical reasons, a diffuser with a fixed first plate length is desirable. Its shape would then be selected to be reasonably efficient in a whole range of Mach Numbers and have maximum efficiency at either the highest Mach Number or at some other critical point dictated by the power-plant requirements. Although recovery appears high in terms of pitot pressure, it must be remembered that the latter drops to low values at high Mach Numbers (at $M = 10$, $p_0'/p_0 = 3/1{,}000$). This is illustrated in Fig. 13 by a plot of diffuser efficiency as defined on the figure. Again the available results of other tunnels are given, and all data appear to lie on a single curve.

No tunnel starting data suitable for direct comparison could be found in the literature.

Finally, the following may be stated: A simple, single peaked throat, variable-area diffuser with plane walls was found to work as well or better than more complicated configurations in the range of Mach Numbers 5.9 to 9.6. In this range of Mach Numbers the pressure recovery of this diffuser was better than that of a pitot tube operated at the same Mach Number. It was found that the essential part of the pressure recovery takes place up to the throat and that viscous effects play an important role in this process. Since neither the parallel plates nor the angle of the diverging section had any significant effect on the pressure recovery, it is concluded that the diffuser section after the throat may be kept short. This minimizes the total heat transfer to the wall for high-temperature operation of hypersonic tunnels. It was also found that hypersonic tunnels may be started at pressure ratios about equal to the pitot pressure ratio, thus making additional starting devices unnecessary. The minimum diffuser throat area at which the shock system could be "swallowed" and supersonic flow could be established was only two-thirds of that predicted by one-dimensional theory in spite of the viscous effects present. Apparently, an oblique shock system is immediately built up during the starting process. The presence of models and supports increased the minimum diffuser throat somewhat but did not materially affect overall pressure ratios.

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